Caribbean Community Climate Change Centre

2016

Potential Study on producible Biogas and Renewable Energy from Biomass and Organic Waste in Belize

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TNO

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31.10.2016

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giz Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH

Japan-Caribbean Climate Change Partnership

From the People of Japan

UNDP Empowered lives. Resilient nations.

Published by Caribbean Community Climate Change Centre, Belmopan, Belize

Digital Edition (October 2016)
Printed Edition (November 2016)

Caribbean Community Climate Change Centre, Ring Road, P.O. Box 563, Belmopan, Belize

Visit our website at http://www.caribbeanclimate.bz

ISBN-13 978-976-8269-05-8 (paperback)
ISBN-13 978-976-8269-06-5 (pdf)

Preface

Dear Readers,

This important study was designed by the Renewable Energy Unit of the Caribbean Community Climate Change Centre and closes the gap of missing waste to energy data for Belize. This study was only made possible through financial contributions by GIZ-REETA (Contract no: 83186954) and with additional co-financing form J-CCCP (UNDP Award no: 00088096). This study matches the sponsor's priority areas which is ***Waste to Energy***.

Waste to Energy has great potential to reduce greenhouse gas emissions significantly and to produce valuable assets. Capturing greenhouse gases like methane on the one side and producing energy in form of electricity and/or heat on the other side is in any case a win win situation; benefiting our environment, energy independency and national finances.

We would like to take this opportunity to express our gratitude and appreciation towards our sponsors GIZ-REETA and J-CCCP, but also to all supporters and consultants who spared no efforts to make this study possible.

Thank you very much.

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Summary

There are large amount of biomass resources available in Belize that have a significant potential to produce biogas. An interesting and suitable use of the biogas in Belize is to convert the biogas in power and heat through a combined heat and power engine. All reported biomass resources have biogas production potential, but every case is different and has to be judged amongst others on its scale (amounts available), easiness of digestibility, alternative uses of the waste, location, etc. For specific biomass resources the following observations are made:

- Municipal waste offers a great potential to produce power and heat; this is the case for both sewer effluent as well as collected municipal solid waste;
- Banana offers a great potential; it is easily digestible, all year round available, and digestion does not produce many different contaminants;
- Shrimp and chicken manure offers a great potential; however, digestion of these wastes result in rather high ammonia concentrations that has to be taken care of;
- Citrus waste offers a huge potential, but in this case it should be kept in mind that practically all of this waste is recycled into different products.

Banana and sewer waste were selected to describe a best practice biogas system. Such best practice system comprises a hammer mill and two mesophilic completely mixed slurry digesters in series with membrane gas storage on top. When banana waste is collected from several farms and the material is digested in a central digester, a production level of 13 Nm^3 biogas per hour can be reached. In a CHP unit this amount of biogas can be converted to electricity and heat, with a production of:

Production of	Power	Heat	Hot water (20 → 95)
Per hour	28 kWh	39 kWh	0.13 kg/s
Yearly	232 MWh	328 MWh	3766 ton

The city of Belmopan currently collects 909 m^3 per day of sewer waste, which is expected to be extended with an additional 590 m^3 per day. From the total of 1500 m^3 sewage per day 263 Nm^3 biogas per day can be produced. In a CHP unit this amount of biogas can be converted to electricity and heat, with a production of:

Production of	Power	Heat	Hot water (20 → 95)
Per hour	23 kWh	32 kWh	0.10 kg/s
Yearly	192 MWh	270 MWh	3106 ton

The recommended system comprises an Upflow Anaerobic Sludge Blanket (UASB) reactor and facultative lagoons.

Contents

Abbreviations

CHP	Combined heat and power
CH_4	Methane
CO_2	Carbon dioxide
COP	Coefficient of performance
H_2S	Hydrogen sulphide
UASB	Upflow Anaerobic Sludge Blanket
UB	University of Belize
VS	Volatile solids
VSS	Volatile suspended solids (organic insoluble matter)

1 Introduction

The government of Belize has outlined a Sustainable Energy Strategy in September 2012. The Ministry of Energy, Science and Technology and Public Utilities (MESTPU) has presented a strategic energy plan and has defined actions and goals on a short and long-term basis. Overall five strategic elements were defined with each element having several goals. The current study 'Potential Study on producible Biogas and Renewable Energy from Biomass and Organic Waste in Belize' contributes at least to several goals of at least two of the strategic elements:

- Strategic Element #2: Reduce the country's dependence on fossil fuels consumption by 50 per cent by 2020
  - Goal #3: Reduce by 50 per cent the number of rural households that use firewood for fuel to other more environmentally friendly biofuels cooking systems such as plant oil and biogas cookers;
  - Action: To implement a Pilot Community Biogas Production Programme in communities with significant livestock;
- Strategic Element #3: To triple the amount of modern energy carriers derived from Agricultural, Forestry and Fisheries production and processing, including municipal solid waste (MSW) by 2020
  - Goal #1: To identify waste material suitable for energy production, the location, availability and quantities
  - Goal #2 and #3: Develop and Implement a Pilot Project Demonstrating Anaerobic Fermentation and Algae Systems that convert organic waste into fuel

Clearly, the current study 'Potential Study on producible Biogas and Renewable Energy from Biomass and Organic Waste in Belize' contributes to these strategic elements and goals since it identifies and maps biomass resources, it determines the biogas potential of these biomass resources (both theoretical and experimentally), and addresses best practice biogas systems all with the aim, in a next phase, to develop and implement a pilot project to demonstrate biogas production.

2 Identify and mapping biomass resources

Based on discussions with the steering committee the following biomass resources were put on a list of potential interesting resources:

- Citrus (remains after juicing to make concentrate)
- Shrimp shells (mostly heads from several aquaculture plants) / Fisheries waste
- Sargassum (seaweed along the Belizean coast and around the islands)
- Banana waste (the left over plant mass after harvesting the fruit)
- Sewer waste (from sewer systems and septic’s)
- Roadside and yard waste (cut grass and trimmings from hedges and trees)
- Chicken manure
- Pig manure
- Cow manure (available in much smaller quantities)
- Leucaena leucocephala invasive species – high in protein: https://en.wikipedia.org/wiki/Leucaena_leucocephala
- Arundo Donax: https://en.wikipedia.org/wiki/Arundo_donax
- Cohune palms: nut and the nut meal (before and after processing)
- Vinasse (liquid waste after distillation)

For most of these resources, details identified related to the amounts, location, and company/ownership are provided in Table 1. The corresponding contact details are provided in a MS-Excel table. Special remarks that have to be taken into account with respect to these resources are given in the next paragraph. The locations of the resources are mapped in a Google map, which can be accessed online as shared online document. A screenshot of the map is given in Figure 1.

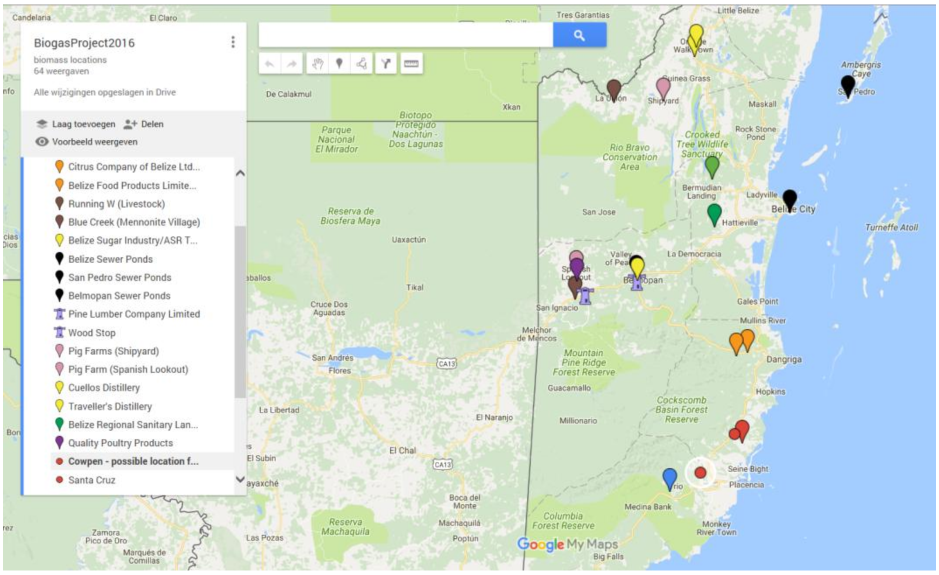

Figure 1: Screenshot of the Google map of resources in Belize.

Table 1: Identified resources, amounts, location, and company/ownership.

Company / Owner	**Type of waste**	**Amount**	**Location**
Belize Water Services	sewer effluent	6818 m^3/day	Belize City
		727 m^3/day	San Pedro Town
		909 m^3/day	Belmopan
Hamland Piggery	pig manure as slurry	~50.4 tons/week	Spanish Lookout, Cayo
Pig Council		188 tons/week	Shipyard, Orange Walk
Mountain View Farm (Hesron Cadle)	Banana and banana stem	14 tons/week	Buena Vista, Stann Creek
Banana Growers Association (BGA)	banana/stems	220 tons/week	Big Creek, Independence
Belize Aquaculture Ltd (Bowen and Bowen)	shrimp heads and shells	8000 tons/year (seasonal)	Blair Athol, Stann Creek
Aqua Mar Belize Ltd (Michael Duncker)			Big Creek, Independence
Paradise Shrimp Farm Ltd			Mi 30, Coastal Rd, Dangriga
Citrus Products of Belize Ltd. (CPBL)/ majority shares by Belize Citrus Growers Association	solid waste stream of citrus peel, pulp, rags and seeds	63.6 thousand tons/8 month processing period	9 Mi Stann Creek Valley Road, Stann Creek
Traveller's Distillery (Romel & Maito Perdomo)	vinasse	182 m^3/week (cyclic 1.5-2 months on, 1 month off)	Forest Drive, Belmopan, Cayo
Cuello's Distillery (Hilberto Cuello)	vinasse		
Belize Livestock Producers Association	cattle manure		47 1/2 Mls Western Highway, Belmopan
Belize Solid Waste Management Authority	municipal solid waste		Belize Regional Sanitary Landfill, 24 Mi George Price Highway
	yard waste	717 tons	
	food scraps	241 tons	
	wood	173 tons	
Quality Poultry	chicken manure	273 tons	Centre Road, Spanish Lookout

Special remarks with respect to the resources:

Banana Waste – Banana Growers Association (BGA)

A typical banana plant takes about 9 months to grow from sprout and produces about 80lbs of banana. Currently, in Belize, there are 24 farms with 9 owners. The smallest banana farm has 80 acres, the largest 700 acres, the average being approximately 320 acres. (2016, Sam Mathias) The Central Bank 2014 Annual Report indicated that the total area of cultivation of banana in Belize, which is concentrated in Stann Creek and Toledo, is 7,162 acres with an average of 791 boxes of bananas/ acre for 2013/2014 (Belize Trade and Investment Zone). Based on values of rejected stems/harvested stems, ~0.5% of stems are rejected. Some bananas from these stems are sold locally by some of the farms. Based on this the average mass, typical annual waste production for all farms, assuming similar efficiency to farm #23 would be approximately 11.5 thousand tonnes of waste per year although amount is likely a bit less since farm #23 does not sell locally. This production is continual. Approximately 19% of this mass is dry weight. The farms are mostly along river banks which have alluvial soils which are considered better for the plants. Concentrated areas of banana farming can be found near Cowpen and Santa Cruz, two communities in Stann Creek.

Banana waste from a sample farm in Mountain View: Farm #24 (Hesron Cadle)
This farm processes approximately 1500 stems/day which produces 1000 boxes of banana equivalent to 40.75 tonnes. It also produces about 2 tonnes waste (stem and bananas)– 5% for an efficiently run farm (Dany Salguero, 2016). This waste banana is often used as cattle feed, the stem is returned to the soil.

Sewer waste – Belize Water Services
Sewage is collected by gravity filtration in zones. Sewage from one zone is pumped to a subsequent zone in a set sequence at the end of which wastewater is finally pumped into 2 cell facultative lagoon system. There are three separate sewer systems in Belize, but the one that is most practical to work with is in the capital – Belmopan. It treats approximately 909 m^3/day but is expected to expand its collection over the next year by an addition of 590 m^3/day.

Shrimp – Belize Aquaculture Ltd
Although there are 8 major farms (Belize Aquaculture Limited, Cardelli Farms, Royal Mayan, Aqua Mar Belize Limited, Bel-Euro Aquaculture Ltd, Tex Mar Ltd, Tropic Aquaculture Investment Ltd, Paradise Shrimp Farms), only two are actively involved in processing shell-less shrimp. The larger of the two is Belize Aquaculture Limited (BAL). BAL estimates that in a typical year, they produce approximately 2.3 million kg of shrimp a year, with ~ 35% waste - approximately 800 tonnes per year. Due to recent EMS outbreak, the production this year (2016) was on 22% of what is normally produced. This degree of effect was seen similarly or to a greater extent in the other shrimp farms. Based on a study by Noel Jacobs (2015), there was an estimated 970 tonnes of wet shrimp waste (head and shells) produced in 2014 from 8 farms. Noel estimated that the waste biomass was approximately 80% water weight. Our experimental assessment of sample provided was 60%.

Citrus waste – Citrus Products of Belize Ltd. (CPBL)
The two citrus processing plants in the country both fall under the auspices of Citrus Products of Belize Limited (CPBL). The main citrus processed at the CPBL includes oranges and grapefruits. Over the past eight months (October – June 2016), approximately 132 thousand tonnes of oranges and 13.5 thousand tonnes of grapefruit were processed at the Belize Food Products Factory. About 3.3 thousand tonnes of oranges and 700 tonnes of grapefruit were rejected. This represents approximately 2.5% and 4.9% rejection for each of the two fruits. The rejected fruits are combined with peel, pulp, rags, and seeds to create a “total solid waste stream” that totals 63,595 tonnes. Practically all of this waste is recycled into different products. During the same 8 month period, approximately 81.5% of the waste stream was processed at the Belize Citrus Feed Plant into citrus pellets for animal feed; 1.8% was transported to Spanish Lookout for Farmers in the area to use to produce their own cattle feed; and the remaining 16.7% was transported to the company’s compost site, to be converted into compost. The compost is intended to be used by local farmers as a soil enhancer. The aim of the company is to process

as much of the solid waste stream from the mill into citrus pellets as it can. The bulk of these pellets are actually exported.

Vinasse - Traveller's Distillery
There are two main distilleries in Belize: Traveller's and Cuellos. At Travellers, the distillation process is cyclic. Distillation is done over a 6-8 week period, then the process is paused for about 4 weeks. During active weeks, approximately 182 m^3 vinasse is produced every 7 days. Currently, the vinasse is diluted with other waste waters produced during processing and then entered into the BWS sewer system. Traveller's initially invested in a set up that would potentially allow biogas generation, but due to their cyclic production process, it was not practical to do continuous biogas production and the idea was abandoned. They have recently joined the West Indian Rum and Spirits Association and under their guidance, are trying to look into other potentially ecologically friendly means of dealing with their waste. Last year, before agreement with BWS, the waste produced by the distillery had built up and overflowed into the nearby River causing concern by the locals.

Pig manure – Hamland Piggery/ Pig Council
Swine inventory in Belize is based on the cess paid to the Belize Livestock Producers Association when the pig is slaughtered at a slaughtering facility. Slaughtering is done every 4 months. Based on the 2014 swine inventory, the current Chairman of the Belize Pig Council, Ernie Thiessen approximates that there are now 24 000 heads. About 75% of the swine is located in Shipyard, a Mennonite community. There are only three farms that host over 1000 heads, one is in Spanish Lookout (Theissen), another Mennonite community, and the others are in Shipyard; although production also occurs to some extent in Barton Creek and Little Belize.

Cattle manure – Belize Livestock Producers Association
According to the Belize Livestock Producers Association (BLPA) 2016 Report published December 2015, the cattle sector has 98 932 heads of cattle based on the last Belize National Sanitary Plan Project (BNSCPP) Cattle Sweep Report. A Livestock Registry is also now in place that will allow tracking of heads. Based on this information, most of the cattle are found in two districts: 48% of the animals are located in the Orange Walk District and 35% in the Cayo District. The remaining 17% is distributed between the other 4 districts. Collection of manure from most farms will be a bit challenging since most farms grow their livestock in open ranches although there are some farms that do have closed stables for cattle and milk cows.

Chicken manure – Quality Poultry/Caribbean Chicken
There are over 350 individual poultry farmers around Belize with varied farm sizes. Quality Poultry, located in Spanish Lookout, is the largest processing poultry plant in the country, processing about half of the chickens in Belize. It has over 130 farmers in the Spanish Lookout region under contract, each with a lot size between 3,000 to 17,000 chickens (about 5,000 on average). A farmer contracted to Quality Poultry will provide a lot every 8 weeks, with two weeks down time for clean-up and disease control. The second largest processor is Caribbean Chicken located in Blue Creek. These two are not only the biggest poultry owners but are also the only ones that have breeders. There is only one rendering plant in Belize and this is run by Quality Poultry. Chicken manure is normally sold locally as fertilizer by individual farmers, sometimes to other industries e.g. Citrus.

Municipal solid waste – Belize Solid Waste Management Authority

The Western Regional Sanitary Landfill is the only Landfill in Belize and services the Western Corridor (from Benque Viejo del Carment to Belize City and including San Pedro and Caye Caulker Islands). Household wastes generated from various municipalities are accessible at the site. Some degree of sorting occurs at the site to remove recyclables (about 1% is recycled based on 2015 report). About 33% of the waste received is organic matter. Values for yard waste, food scraps and wood were generated using composition break down from the Waste Generation and Composition Study conducted by the Belize Solid Waste Management Authority (SWMA) in 2011 and recorded tonnage received from the Western Corridor for 2016 by SWMA.

3 Biogas potential of biomass resources

3.1 Biogas potential – laboratory tests

The biogas laboratory located at the University of Belize (UB) was contracted to perform the tests to determine the biogas potential of local available resources. Six biomasses can be tested at the same time. Biomasses selected for the first lab test series were:
- Cohune nut meal (processed)
- Cohune nut meal (unprocessed)
- Banana waste (stalk)
- Whole bananas
- Leucaena leucocephala
- Local fish waste – shrimp heads and shells

These samples were obtained as follows by UB:
- A small village in the Belize District, Flowers Bank, was visited where there is a cooperative that collects cohune nuts and makes oil; some of the ground meal (processed and unprocessed) was purchased;
- One of the 24 banana plantations in the South was visited; some of their waste was obtained, which is in fact mainly rejected banana and stalk - leaves are actually left on the plantation to allow them to mulch;
- Samples of shells and heads were obtained from one of the major shrimp farms that does deshelling;
- Samples were taken of a Leucaena plant that grew nearby (mainly leaves and ribs).

The samples were mixed with cow manure, home grown sludge, the source of bacteria that should digest the biomass resources. Initially the tests went well: gas was being produced, the cow manure worked, although a little bit slowly. The gas production in each bottle looked very much like gas production in the cow manure bottle (which was expected), except for cohune samples, which clearly gave lower values: this may indicate that cohune contains compounds that inhibit the biological activity.
After the initial test period, problems with gas analysis began to occur. Gas analyses gave strange readings; showing significant quantities of oxygen being present in the produced gas. When there is indeed oxygen, the experiments may underestimate the gas production since in that case the samples may have been exposed (partly) to aerobic conditions. Initially, it was hypothesized that the anomaly was caused by a malfunction of the gas analyzer and/or nitrogen generator. Further analysis suggested that the problem was caused by the method of sampling in combination with the analyzer mode setting – it needs a certain amount of flow/pressure for proper reading, insufficient flow or pressure may attract air from the environment. The supplier of the analyzer proposed application of a special procedure, called Small Volume Methodology. This method did not improve reading as was anticipated. Therefore, it was decided that the analyzer be sent back to TNO to check its performance as well as to perform a calibration at the supplier.
Meanwhile, another problem developed, this time with the sample bags. After three months of use, most of the sample bags appeared to have garnered holes. Due to

the problems encountered, measurements were delayed and the data was no longer considered accurate. It is proposed that the initial test procedure will be modified to reduce occurrence of holes: samples will not be shaken (a possible cause of the holes). One series of lab testing will be repeated and the results will be added as appendix or extra memo later on to this report. Testing will start when the analyzer is returned to UB.

3.2 Biogas potential – literature values

Method

Biogas is produced from organic matter in biomass. Minerals are not converted into biogas and some organic compounds are not converted either, with lignin as the most relevant example. The maximum theoretical biogas potential can be calculated from the organic matter content minus lignin. The organic matter content and composition of the main organic constituents can be found in literature and data-bases available at TNO.

In reality, the actual biogas yield can be lower since constituents such as the lignocellulose complex are poorly accessible to micro-organisms and their enzymes. These actual biogas yields may be available in literature in papers of researchers that already tried biogas production from the particular biomass that has been selected for this study. If this information is not available an educated guess is made regarding a realistic actual biogas production potential.

The method of estimation is described below.

The main constituent in our selected biomass types are polysaccharides (cellulose, hemicellulose, pectin, starch), except for the shrimp shells.

Polysaccharides are first hydrolysed into monosaccharides and subsequently converted into methane and carbon dioxide:

$(C_6H_{10}O_5)n + n\ H_2O \rightarrow n\ C_6H_{12}O_6$

$C_6H_{12}O_6 \rightarrow 3\ CH_4 + 3\ CO_2$

Note that the amounts (moles) of methane and carbon dioxide are equal.

Protein will produce slightly more methane, slightly less carbon dioxide but in addition also ammonia and sulfide. Fats and oils will produce much more methane than carbon dioxide. Fats are first hydrolysed into glycerol and fatty acids. Both are converted into methane and carbon dioxide. An example is given for a fatty acid:

$2\ CH_3(CH_2)_{14}COOH + 14\ H_2O \rightarrow 23\ CH_4 + 9\ CO_2$

Literature sources generally do not describe the composition of the complete organic matter, only the main constituents, which mean that the nature of a part of the organic matter is unknown.

A part of the organic matter in biogas is used to produce new bacterial biomass. About 10% is used for that purpose. That means that the maximum theoretical biogas yield involves only 90% of the biodegradable organic matter.

A part of the carbon dioxide does not end up in the gas, but dissolves in the water. The exact amount depends on the properties of the water and the gas, such as pH, temperature and gas pressure. Methane only dissolves in very small amounts in the water phase. In general, and on average, biogas contains 60% methane.

Taking all these effects in account, it is proposed here to use the methane production data connected to polysaccharides for the complete organic matter minus lignin. 1 kg cellulose or starch produces after hydrolysis 1.1 kg glucose. About 10% of that amount is used for bacterial growth, which leaves about 1 kg glucose for biogas production, which is (3 x 16/180) = 0.267 kg methane, which is 0.374 Nm^3 methane or (if 60% is methane) 0.62 Nm^3 biogas. Nm^3 are normal cubic meters at a temperature of 0˚C and a pressure of 1 bar (ambient pressure). At a higher temperature, the biogas volume expands: 0.62 Nm^3 is 0.68 m^3 at 25˚C.
In summary, the rule to calculate the biogas potential of a certain biomass is: the maximum theoretical biogas yield in Nm^3 is 0.62 times the weight in kg of the organic matter minus the lignin.

Citrus waste
In literature the composition of citrus peels can be found. A summary is given in Table 2.

Table 2: Composition of orange and lemon peels.

Moisture (% of fresh)	% of dry matter							Literature source
	Ash	lignin	cellulose	hemicellulose	pectin	protein	fat	
	4.6							Phyllis2
	1.5 – 1.9	1.7 – 2.1	12.7 – 13.6	5.3 – 6.1				Ververis, 2007
84.6	2.8	2.2	11.9	14.5		6.0		Sánchez-Orozco, 2014
76		5.0	16.4	6.7				Vellingiri, 2014
		0.6	12.8	7.1	5.7			Ahmadi, 2015
40.7	7.4	6.4			7		1.9	Irshad, 2014
	1.5 – 3.7	0.8 – 7.5	9 - 37		21 - 42	6 - 9		Nazari Chamaki, 2013

In Table 2 the study of Nazari Chamaki (2013) involved information of 7 other studies. From Table 2 it can be concluded that the dry matter of citrus peels contains about 3.3 % ash, which means 96.7% organic matter. The dry matter also contains about 3.3% lignin. It is also clear that about half of the organic matter is polysaccharide, the other part comprises protein, fats and most probably organic acids, other sugars and terpenes.
Therefore, the maximum theoretical biogas yield per ton of citrus peel dry matter is:
0.62 x 1000 x (0.967 – 0.033) = 579 Nm^3
The moisture content varies, but at an average of 67%, the maximum theoretical biogas yield per ton of fresh peels is 191 Nm^3.
In laboratory studies with anaerobic digestion of orange peels lower amounts of biogas are found. The problem is the presence of D-limonene in orange peels, an anti-microbial agent that inhibits anaerobic digestion. Wikandari et al. (2015) calculated a maximum theoretical methane production of 0.45 Nm^3 methane per kg

VSS, which may be 0.75 Nm^3 biogas per kg VSS or 0.73 Nm^3 biogas per kg dry matter, which is higher than we have estimated. VSS is volatile suspended solids, in fact the organic insoluble matter. Chopped peels produced 0.06 Nm^3 methane per kg VSS, homogenized peels 0.131 Nm^3 per kg VSS and chopped and hexane-extracted peels (to remove limonene) 0.217 Nm^3 per kg VSS. Assuming that the methane yield of insoluble organic matter and soluble organic matter are comparable, this translates to about 209 Nm^3/ton dry matter. Martin (2010) used steam distillation to remove D-limonene and the residue was tested in anaerobic digesters. The methane yield found was 0.230 Nm^3 methane per kg VS (volatile solids) under mesophilic conditions and 0.332 Nm^3 methane per kg VS, which translates to 222-321 Nm^3 biogas per ton orange peels dry matter.
Summary: actual biogas potential of orange peels after limonene extraction can be about 270 Nm^3/ton dry matter, or 89 Nm^3 per ton fresh peels.

Banana waste
A summary of literature data on the composition of banana plant waste is given in Table 3.
Banana waste with about 16% ash (which means 84% organic matter) and 15% lignin may have a maximum theoretical biogas yield of 620 x (0.84 – 0.15) = 428 Nm^3 per ton dry matter. According to the Banana Growers Association banana plant residues have a dry matter concentration of 19%. In November 2015, the University of Belize, in cooperation with TNO, has determined a 17% dry matter content in banana leaves, which is near to that value. The first percentage (19%) can be used to calculate a maximum theoretical biogas yield of 81 Nm^3 biogas per ton fresh matter.

Table 3: Composition of banana residues.

Type	% of dry matter								Literature source
	Ash	Lignin	Cellulo-se	Hemi-cellulose	Holo-cellulose[a]	Protein	Lipids	Starch	
Banana leaves	7.7	22.5	23.8				17.5		Phyllis2
Banana sheets	16.4	7.2	35.5	14		2.6			Phyllis
Banana stem	1.5	18.6	63.9						Abdul Khalil, 2006
6 different parts of banana plant	11.6-26.8	10.5-24.3			20-65				Mohapatra, 2010
Leaves and rachis	19-26.8	9.6-12.6			37.9-49.7	1.9-2.0		1.4-8.4	Oliveira, 2008

[a] *Holocellulose means cellulose plus hemicellulose.*

Actual biogas yields can be found in laboratory studies. Kalia (2000) found 269 l biogas per kg banana stem dry matter in mesophilic digesters and 220 l under thermophilic conditions. The methane content of the biogas at the end of the fermentation time was about 60%. Bardiya (1996) found 219 l biogas per kg banana peel dry matter. Kamdem (2013) found 240 l biogas from a kg banana leaves sheets dry matter, 155 l from a kg leaves blades DM and 280 l from a kg rachis stems DM. Here an average is proposed of 210 Nm^3 biogas per ton banana waste dry matter or 40 Nm^3 per ton fresh matter, including in the calculation a correction from actual m^3 to normal m^3.

Arundo donax

The composition of *Arundo donax* (giant reed) can be found in literature and is summarized in Table 4. A distinction is made between nodes (the part of the stem to which the leaves are attached), the internodes (the stems between two nodes) and the leaves (foliage).

Table 4: Composition of Arundo donax.

Plant part	Moisture (% of fresh)	% of dry matter					Literature source
		ash	lignin	cellulose	hemicellulose	protein	
Whole	42	3.4					Phyllis2
Whole	36.1	3.6					Phyllis2
Foliage		5.8	16.8	43.8	27.4	2.1	Phyllis2
Internode		3.8	19.4	26.6	25.7	2.9	Phyllis2
Node		3	17.7	28.3	28.3	3.0	Phyllis2
Node		5.1	18				Ververis, 2004
Internode		4.7	18				Ververis, 2004
Whole	36-50						Bacher, 2001

With an average of 4.2% ash (or 95.8% organic matter) and 18% lignin, the maximum theoretical biogas yield is 620 x (0.958 – 0.18) = 482 Nm^3 per ton *Arundo donax* dry matter. At a moisture content of 40%, which is 60% dry matter content, the maximum theoretical biogas yield is 289 Nm^3 per ton fresh matter. Actual biogas yields again can be found in laboratory studies. Ragaglini (2014) found yields ranging between 0.258 Nm^3 methane/ kg VS and 0.392 Nm^3/ kg VS in old and young plants respectively. The young plants contain less lignin and are better digestible. Di Girolamo (2013) found 0.273 Nm^3 methane/ kg VS. On average, and calculating with 60% methane content and 95.8% VS, the actual biogas yield in old (mature) plants is about 424 Nm^3/ ton *Arundo donax* dry matter (254 Nm^3 per ton fresh matter).

Cohune palm nut meal

The nuts from the cohune palm are pressed to produce oil. The crushed residue is the meal. No composition data could be found on this type of biomass, nor experience with biogas production. However, the composition may not be very far from defatted peanut flour. That contains 7.8% water. The dry matter comprises 38% carbohydrates, 57% protein, 0.5% fat and 5% ash (http://nutritiondata.self.com/facts/legumes-and-legume-products/4367/2). That is about 95% organic matter that is largely digestible. The theoretical biogas yield is 620 x 0.95 = 589 Nm^3 biogas per ton defatted nut meal dry matter. This is about 353 Nm^3 methane per ton defatted nut meal dry matter.
Cohune palm nuts contain 63% - 70% oil (Wickens, 2004). The biogas yield from oil is much higher than that from carbohydrates. About 2.5 times more methane is

produced and the biogas contains a higher percentage of methane. The dry matter of unprocessed nut meal may contain 67% oil and 33% of the matter described above. The theoretical methane yield is: 0.33 x 353 + 0.67 x 2.5 x 374 = 743 Nm^3 methane per ton unprocessed cohune nut meal dry matter. The methane content of biogas produced from such fatty biomass may be 75%, which means 991 Nm^3 biogas may be produced from a ton unprocessed cohune nut meal dry matter.

Local fish waste and shrimp heads

Average fish meat contains 78% water, 17% protein and 2% fat (www.tankonyvtar.hu). Bones contain protein (collagen), fat and minerals (calcium, phosphate). Shrimp meat contains 79% water, 18.1 % protein and 0.8% fat. The shell of shrimps is made of chitin, a carbohydrate.

Fish waste is a mixture, and it depends very much how this mixture is composed. As an educated guess a composition of 75% water, 19% protein, 3% fat, 1% carbohydrates and 2% ash is proposed. From the organic matter, in which protein is dominant, 0.38 kg methane can be produced, but a part of the organic matter is converted into bacterial mass. The actual methane production may be 0.34 kg which is 0.48 Nm^3 methane or (if 60% is methane) 0.79 Nm^3 biogas.

The dry matter of fish waste contains 92% organic matter. One ton fish waste dry matter can theoretically produce 0.92 x 790 = 727 Nm^3 biogas.

One ton fresh fish waste can theoretically produce 182 Nm^3 biogas.

These data will not be very far from the data for shrimp heads only.

Fish protein contains 18% N. When the NH_4-N concentration in a digester is higher than 4 g/l, the digestion process is strongly inhibited. Therefore, the fish part (fresh weight) of the input cannot be more than 12% of the total weight of the input. The rest must be water or other residues (poor in nitrogen).

Road side green and yard waste

Verge grass and bushes mainly contain lignocellulose. According to the phyllis2 data-base verge grass dry matter contain 13% ash and 26% lignin. The remaining organic matter is mainly cellulose and hemicellulose. The maximum theoretical biogas yield can be estimated as 620 x (0.87 – 0.26) = 378 Nm^3 per ton dry matter. TNO's own experiments with nature grass and park grass anaerobic digestion yielded between 100 -175 Nm^3 per ton dry matter. The material is clearly recalcitrant to anaerobic digestion because lignocellulose is a strong inaccessible complex. A thermal treatment (steam) of the grass before anaerobic digestion resulted in 325 – 375 Nm^3 biogas per ton dry matter. Thermal treatment opens the lignocellulose structure and improves the accessibility to enzymes.

Manure

According to the phyllis2 database cattle, pig and chicken manure (complete) contains on average 28%, 21% and 24% ash respectively. According to Kool (2005) the ash contents are 26%, 33% and 40%. For our calculation it is proposed to take the average of these data: 27%, 27% and 32% ash in cattle, pig and chicken manure respectively (complete/slurry).

According to Chen (2003) cattle, pig and chicken manure contains respectively 13%, 4% and 5% lignin based on dry matter.

The maximum theoretical biogas yield is estimated using the data above: 372, 428 and 391 Nm^3 biogas per ton dry matter for cattle manure, pig manure and chicken manure respectively.

In reality, the amount of biogas produced from manure is much lower, since manure still contains poorly digestible fibers. Kool (2005) summarized the biogas production found at various places in the Netherlands (Table 5).

Table 5: Observed biogas production from manure (Kool, 2005).

Manure type	Dry matter content (g/kg fresh)	Organic matter content (g/kg fresh)	Methane yield (m^3/ kg organic matter)	Calculated biogas yield (Nm^3/ton dry matter)*
Cattle slurry	86	64	0.12 - 0.21	138 – 243
Cattle solid	248	150	0.12 - 0.20	113 – 188
Chicken	670	400	0.21 - 0.30	195 – 280
Pig slurry	55 - 90	35 - 60	0.14 - 0.30	145 – 310
Pig solid	230	160	0.22 - 0.30	238 - 222

* biogas with 60% (v/v) methane assumed

In the report Waste-to-Energy Scoping Study for Grenada (Rothenberger, 2015) an estimation of the amount of methane produced per ton of fresh matter of a 6% TS (total solids, same as dry matter) pig manure slurry is given: 11.5 Nm^3 methane/ton fresh matter. This would be about 319 Nm^3 biogas/ton dry matter, which is near to the maximum given in Table 5.
Other data on biogas production from cattle manure (not separated in slurry/solid) mono-digesters can be obtained from Dutch and German literature sources, see Table 6.

Table 6: Data on biogas yields from cattle manure mono-digesters (numbers in red are calculated by Van Groenestijn).

Dry matter content (%)	Organic matter as percentage of dry matter	Biogas yield per ton fresh manure	Biogas yield per ton dry matter	Biogas yield per ton organic matter	Methane yield per ton organic matter	Percentage methane in biogas	Source
		22 Nm^3/ton				55	Projectvoorstel Universiteit van Utrecht 2013; confidential
8	80	13.5 Nm^3/ton	169 Nm^3/ton	210 Nm^3/ton	124 Nm^3/ton	59	Haalbaarheids-studie Bergam-bacht (2010)
8 - 11	75 - 82	20 - 30	250 – 273 m^3/ton	Ca 316 m^3/ton	Ca 190 m^3/ton	60	Handreichung Biogas-gewinnung, FNR 2006
8.8	85	21.0 Nm^3/ton	239 Nm^3/ton	281 Nm^3/ton	154 Nm^3/ton	55	Handreichung Biogas-gewinnung, FNR 2006
					120 – 210 m^3/ton		Kennis-bundeling covergisting: Kool 2005

Organic household waste
Organic household waste is composed of organic residues from kitchen and garden. The variation of the composition may be large, but at least an estimation is given here. TNO's own measurements on this type of waste of a particular sample given by Orgaworld and collected by the city of Drachten (the Netherlands) in autumn 2014 indicated 38% dry matter and an ash content of 27% based on dry matter. The lignin content is not known, but may be near 8%, while the carbohydrate content will be high. Using these data a maximum theoretical biogas production of 403 Nm^3 per ton dry matter can be calculated.
In reality the biogas production is lower. In 1992 an investigation was made on 10 different European biogas digester types that were running on pilot or full scale and using organic household waste (Jong, 1993). The biogas production ranged from 40 to 140 Nm^3 biogas per ton fresh matter, with 101 Nm^3 as an average. This would correspond to 266 Nm^3 biogas per ton dry matter. The average methane content was 62%.

Leucaena
The leaves and seeds of *Leucaena leucocephala* may be used for biogas production. The more woody parts should be avoided. However, it will be impossible to avoid the twigs. According to Aung (2007) *Leucaena* leaves dry matter contain 91% organic matter and according to Jama (1996) the leaves contain 5.4% lignin (based on dry matter) and the twigs 10.8%. It can be calculated that from a mixture of 75% leaves and 25% twigs a maximum theoretical amount of biogas as much as 522 Nm^3 per ton dry matter can be produced. No data on the actual biogas production from *Leucaena* leaves could be found, but since the amount of lignin is not as high as verge grass or banana leaves and resembles more that of organic household waste (which also contains a lot of leaves), the amount of (recalcitrant) lignocellulose will also be more comparable to household waste. As can be seen from the household waste section, the ratio between actual and theoretical maximum biogas yield is about 2/3 (or 266/403). Similarly the actual biogas production from *Leucaena* may be 2/3 of the maximum theoretical: 348 Nm^3 biogas per ton dry matter.

Vinasse
Vinasse is the remaining slurry from the bottom of an ethanol distillation column in the process of production of ethanol from sugar cane. Moraes (2015) studied 11 experiences with vinasse anaerobic digestion. The COD of the vinasse ranged from 10 – 130 g/l. For now it is proposed to use 30 g/l as an average. The average COD removal was 74% and the observed methane production ranged around the theoretical 0.35 Nm^3 /kg $COD_{removed}$. This would mean that 30 x 0.74 x 0.35 = 7.8 Nm^3 methane is normally produced from a m^3 bagasse. Assuming a methane content in biogas of 60% and a vinasse density of 1 ton/m^3, about 13 Nm^3 biogas can be produced per ton vinasse.

Sewage and septage
In the report Waste-to-Energy Scoping Study for Grenada it is stated that in the Caribbean region sewage contains 200-250 mg BOD/l and 350-450 mg COD/l. Normally not all COD is converted into biogas, however, it will be more than only the BOD. Using 75% COD conversion and 0.35 Nm^3 methane /kg $COD_{removed}$ and a

biogas methane content of 60%: 0.4 kg COD/m^3 sewage x 0.75 x 0.35/0.6 = 0.175 Nm^3 biogas per m^3 sewage is produced. This is not far from the 0.1 Nm^3 methane/m^3 (which may be 0.17 Nm^3 biogas/m^3) mentioned in the Grenada study (Rothenberger, 2015).
Septage may be another source for biogas production. It is the residue (sludge) from septic tanks which accumulates in time and has to be removed at timely intervals. According to information from the Grenada study septage contains 3,000 – 5,000 mg BOD/l and 25,000 – 40,000 mg COD/l. A large part of the COD is present in suspended solids. No data are available on biogas production from septage, and it must be mentioned that the use of this material for that purpose is not completely logic. Septage is the residue left after an anaerobic digestion process and after solubilized compounds have been leached out (to the surrounding soil). Therefore, only a small part of COD will be biodigestible and probably hardly more than the BOD value. Our educated guess is a conversion of only 7000 mg COD/l. That will yield 7 kg COD/m^3 septage x 0.35 = 2.5 Nm^3 methane (or 4.2 Nm^3 biogas) per ton of septage. In the Grenada report an estimated 4 Nm^3 methane per m^3 septage is given.

Sargassum
Sargassum is a seaweed belonging to the macro-algae. According to Abou-el-Wafa (2011) *Sargassum subrepandum* contains 29% ash (based on dry matter) and according to Oliveira (2015) *Sargassum sp.* contains 54% organic matter. When using an average 63% organic matter, the maximum theoretical biogas production may near 390 Nm^3 per ton dry matter.
Oliveira (2015) tested biogas production in a laboratory, using the *Sargassum sp.* mentioned above. The production was 181 l methane per kg COD, measured at 37˚C, while the COD content of the seaweed was 0.6 kg per kg dry matter. Assuming 60% methane in biogas and recalculating the volume to standard conditions, a yield of 0.6 x 181 x 273/(273+37)/0.6 = 159 Nm^3 biogas/ton sargassum dry matter can be calculated. According to Oliveira this corresponds to 52% of the theoretical maximum, which is in line with our calculation.

Summarizing table
The values found are summarized in Table 7.

Table 7: Summary of biogas yields.

Biomass type	Maximum theoretical biogas yield		Biogas yield found in practice		% DM in fresh matter
	Nm^3/ton DM	Nm^3/ton fresh matter	Nm^3/ton DM	Nm^3/ton fresh matter	
Citrus waste	579	191	270	89	33
Banana waste	428	81	210	40	19
Arundo donax	482	289	424	254	60
Cohune palm nut meal, defatted	589				92 [1)]
Cohune palm nut meal	991				92 [1)]
Fish waste and shrimp heads	727	182			25
Road side green and yard waste	378		100-175		30 [2)]
Cattle manure slurry	372	37	138-273	12-30	8-11
Pig manure slurry	428	30	145-310	10-22	7
Chicken manure	391	262	195-280	131-188	67
Organic household waste	403	250	266	101	62
Leucaena	522		348		38 [3)]
Vinasse	325	13			4 [4)]
Sewage	350	0.175			0.05 [5)]
Septage	105	4.2			4 [6)]
Sargassum	390		159		16 [7)]

[1)] Based on defatted peanut flour;
[2)] Based on TNO experience in the Netherlands;
[3)] Based on data for Dutch garden waste;
[4)] Based on not-concentrated vinasse including some inorganics (with 30 g COD/l);
[5)] Based on 400 mg COD/l plus some organics;
[6)] Based on 37 g COD/l plus some inorganics;
[7)] Obtained from BIOS report: 16% DM after dewatering by gravitation; 30% DM can be reached after active dewatering with dedicated equipment.

3.3 Energetic calculations

A calculation tool was developed in MS-Excel to calculate the energetic content of the various identified biomass resources. A screenshot of the tool is given in Figure 2. The calculation of the energetic content is based on the biogas yields from the identified biomass resources, as summarized in Table 7. The tool uses the values for the biogas yield found in practice, unless no values were found – in that case the tool uses the theoretical values. The theoretical values are always higher than the values found in practice, implying that these values give an overestimate of the methane produced, and consequently an overestimate of the produced power and heat. The user has to provide the biomass input as fresh biomass. The user may define two biomass types to calculate the energy output of a mixture. Note: the calculation tool does not provide feedback whether or not it makes sense to mix the chosen biomass. The calculation converts this fresh biomass to biomass dry matter based on a percentage dry matter, which is provided under the data sheet 'Digestion' in the tool. Since only the organic part of the dry matter is converted to methane, this is the most straightforward way to convert biomass via methane towards heat and power. The biogas yield found in practice (see Table 7) is provided per unit mass of dry matter, and together with the amount of dry matter this is converted to biogas production in Nm^3 per hour. The produced biogas is corrected for the methane content, resulting in a total 'heat' (or 'energy') input by multiplying with the heating value of methane, 35.8 MJ/Nm^3. Depending on the chosen CHP engine (see next paragraph) the total produced power and heat are calculated, taking into account the electrical and thermal efficiencies belonging to the chosen engine. The total production of power and heat is also calculated per year while taking into account the commercial availability of the engine. The latter is standard set at 95%. Finally, the amount of hot water is calculated that can be produced from the heat output, assuming the water is heated from 20°C to 95°C.

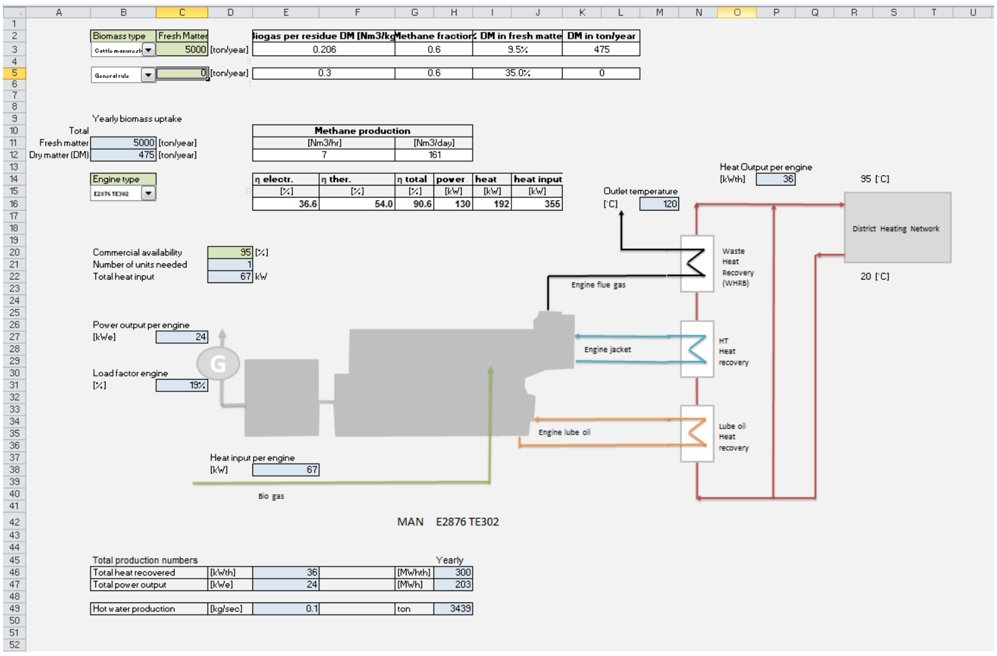

Figure 2: Screenshot of the energetic calculation tool.

CHP engines

Combined heat and power (CHP) engines, so-called cogeneration units, convert digester biogas in an internal combustion engine (ICE) into electricity and heat. This heat is extracted from the engine and can be used for space heating, water heating and industrial steam.
The combined electricity and heat is generated in an efficient way and CHP units are often more than 80% efficient. CHP units normally run on natural gas. They can also run on methane coming from biogas recovery systems from waste products which are potentially available in Belize.
A survey was carried out to be able to choose the appropriate engine for biogas conversion. There are many large players in the field of internal combustion engines. Main suppliers are GE (Jenbacher), MWM, MAN, and 2G. Engines run at a typical speed rotation per minute at variable load conditions. For Belize 60 Hz is assumed as starting point for assessing the performance parameters, which are listed in Table 8. All engines have a total efficiency of more than 80% (only one exception), in various combinations of efficiencies for power and heat. Furthermore, in all cases the NO_x emissions are below 500 mg/Nm^3.

Table 8: CHP engines for biogas.

Engine sheet											
			NOx	η electr.	η ther.	η total	power	heat	heat input	Outlet temp.
nr	Supplier name	type	[mg/Nm3]	[%]	[%]	[%]	[kW]	[kW]	[kW]	[°C]
1	GE	J312	<500	38.1	48.8	86.9	633	811	1661	180
2	GE	J316	<500	38.3	48.9	87.2	849	1084	2217	180
3	GE	J324	<500	39.1	48.6	87.7	1062	1320	2716	180
4	MWM GEN SETS	TCG 2016 V08 C	<500	41.5	43.9	85.4	400	423	964	150
5	MWM GEN SETS	TCG 2016 V12 C	<500	41.3	44.4	85.7	600	645	1453	150
6	MWM GEN SETS	TCG 2016 V16 C	<500	41.6	44	85.6	800	846	1923	150
7	MWM GEN SETS	TCG 2020 V12 C	<500	41.5	43.9	85.4	1200	1269	2892	150
8	MWM GEN SETS	TCG 2020 V16 C	<500	41.1	44.1	85.2	1550	1663	3771	150
9	MWM GEN SETS	TCG 2020 V20 C	<500	41.5	43.7	85.2	2000	2106	4819	150
10	MAN	E0836 LE202	<500	38.6	53.7	92.3	110	153	285	150
11	MAN	E2876 TE302	<500	36.6	54	90.6	130	192	355	120
12	MAN	E2876 LE302	<500	39.1	50.8	89.9	200	260	512	120
13	MAN	E2676 LE212	<500	40.3	46.4	86.7	250	288	620	120
14	MAN	E2848 LE322	<500	37.7	51.9	89.6	295	406	782	120
15	MAN	E3268 LE222	<500	40.8	47.9	88.7	390	458	956	120
16	MAN	E3262 LE212	<500	38.9	51.6	90.5	580	769	1491	120
17	2G	FiliUS 104	<500	35.3	49.8	85.1	50	71	142	120
18	2G	FiliUS 106	<500	38	45.8	83.8	150	181	395	120
19	2G	FiliUS 206	<500	38.2	38.2	76.4	52	52	136	120
20	2G	FiliUS 107	<500	35.3	49.8	85.1	53	75	150	120
21	2G	FiliUS 108	<500	35.3	49.8	85.1	54	76	153	120
22	Smartblock	SB16	<500	30.8	72	102.8	16	37	52	100
23	ESS Viessmann	EM-50/81	<500	34.4	55.8	90.2	50	81	145	120

To get an indication what the potential is in Belize to produce power and heat from the available biomass resources, Table 1 and Table 7 are combined and the result is shown in Table 9. The total produced power, heat and hot water is calculated from the amount of biomass resources. The following observations are made:

- Municipal waste offers a great potential to produce power and heat; this is the case for both sewer effluent as well as collected municipal solid waste;
- Banana offers a great potential; it is easily digestible, all year round available, and digestion does not produce many different contaminants;
- Shrimp and chicken manure offers a great potential; however, digestion of these wastes result in rather high ammonia concentrations that has to be taken care of;
- Citrus waste offers a huge potential, but in this case it should be kept in mind that practically all of this waste is recycled into different products.

Table 9: Power and heat potential from the available biomass resources in Belize.

Company / Owner	**Type of waste**	**Amount tons / year**	**Power kWh per hour**	**Heat kWh per hour**	**Hot water kg/h**
Belize City	Sewer effluent	2488570	105	148	1696
San Pedro Town	Sewer effluent	265355	11	16	181
Belmopan	Sewer effluent	547500	23	32	373
Hamland Piggery	Pig manure as slurry	2621	10	14	163
Pig Council	Pig manure as slurry	9776	37	53	606
Mountain View Farm (Hesron Cadle)	Banana and banana stem	728	7	10	113
Banana Growers Association (BGA)	Banana and banana stem	11440	110	155	1778
Belize Aquaculture Ltd	Shrimp heads and shells	8000	350	493	5664
Citrus Products of Belize Ltd. (CPBL)	Solid waste stream of citrus peel, pulp, rags and seeds	63600	1363	1922	22073
Traveller's Distillery	Vinasse	9455	30	42	479
Belize Solid Waste Management Authority	Municipal solid waste:				
	Yard waste	37284	371	524	6012
	Food scraps (OHW)	12532	497	701	8050
Quality Poultry	Chicken manure	14196	544	768	8817

* Calculation based on Engine 2G FiliUS 107

4 Best practice biogas systems

4.1 Production of biogas from banana residues

In our inventory we found that currently 24 banana farms are operating in Belize by 9 owners. These 24 farms together produce 220 tons of residues per week, with a dry matter content of 19%. These residues are rejected bananas and banana stems (Figure 3). The rejected bananas are used as cattle feed and the stems are returned to the soil. Our proposal is to use the stems for biogas production and continue to use the bananas as cattle feed. It is expected that a small part of the farm residues are banana tree leaves. These can be used for biogas production as well. Let us assume 170 tons of stem and banana leaves weekly with average 19% dry matter content.

Figure 3: Banana stems (adopted from www.adinaturals.com).

In our estimation, based on literature values, a production of 210 Nm^3 biogas can be expected from one ton banana waste dry matter. The observed methane content was 60% (v/v). However, the maximum theoretical biogas production (conversion of all biodegradable compounds except lignin) is 428 Nm^3 per ton dry matter. The difference is caused by presence of recalcitrant lignocellulose in the stems and leaves. The ash content of stems and leaves is about 16%.
170 tons/week by 24 farms means an average of 7 tons/week per farm. Therefore, the expected biogas production is 7 tons/week x 0.19 x 210 Nm^3 biogas/ton DM = 279 Nm^3 biogas per week = 40 Nm^3/day = 1.7 Nm^3/h. This is small for a biogas plant and it should be considered to collect banana waste from several farms and digest the material in a central digester. Most farms are concentrated in the Toledo District and the adjacent Stann Creek District. It must be possible to collect the residues from 8 farms within a circle of 30 km around the biogas plant. This way it may be possible to collect 56 tons of residues per week and produce 13 Nm^3 biogas per hour. When this amount of produced biogas is converted to electricity and heat in a CHP unit, for example the CHP from 2G type FiliUS 107, the following output is generated:

Table 10: Energy production of the proposed system banana waste collected from 8 farms.

Production of	Power	Heat	Hot water (20 → 95)
Per hour	28 kWh	39 kWh	0.13 kg/s
Yearly	232 MWh	328 MWh	3766 ton

Because of the before mentioned properties the biogas production system will be characterized by the following:

- Due to the size of stems and leaves particle size reduction is required to give the bacteria and enzymes a better excess to the material
- Because of the low dry matter concentration, digestion systems based on slurries (wet) should be chosen, rather than dry digestion (35% DM).
- In the selection of the destination of the digestate it should take into account that more than half of the organic matter will not be converted in the digester.

Collection and storage

A truck can transport 20 tons of residues; therefore such truck may collect the week storage of 3 farms in one day and spent two other days for the other 5 farms. The farms should store the stems and leaves on a heap or in a pit both covered with a plastic cover. The cover is required to prevent a flow of air through the heap and subsequent composting (loss of biodegradable substrate). Ensilage (biological acidification) is welcome but not obligatory. The week amount at each farm is on average 7 tons. It excludes the rejected bananas: these are used for cattle feed.

At the biogas plant the full amount of 20 tons is directly chopped and introduced in the digester. This immediate processing prevents too much storage and handling.

Hammer mill

A 5 ton per hour hammer mill is required to chop the large pieces into pieces with the size of about 2 mm. The chopping is carried out by rotating hammers (Figure 4). A hopper can be placed on top of the mill in order to feed the mill continuously.

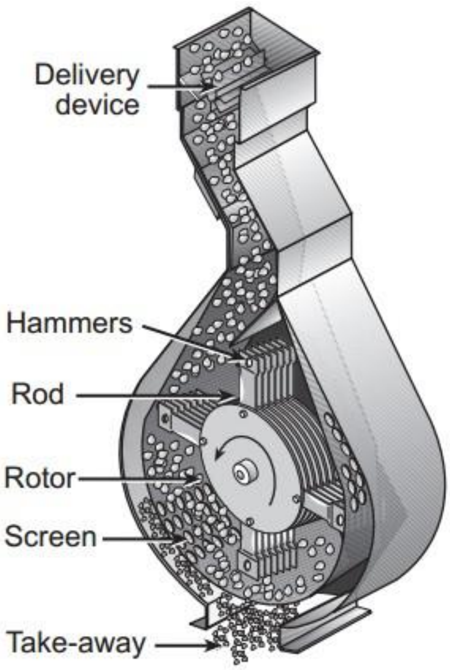

Figure 4: Hammer Mill (adopted from www.crusherindustry.com).

Digester

As far as we know no full scale dedicated banana residues digesters exist. Only laboratory experiments are known (Bardyia et al., 1996; Kalia et al., 2000; Kamdem et al., 2013). From these experiences it seems that the material can be digested well within 25 days at a temperature of 37°C and that a slight dilution, i.e. lower dry matter concentrations than 19%, stimulates biogas yield. Furthermore, a banana residue digestion may be close to SWILL (kitchen waste) digestion, source separated organic fraction of municipal waste digestion and manure/codigestion.

Mesophilic digestion is preferred. The advantages over thermophilic digestion are: (1) higher stability, less sensitive, (2) lower energy requirement and (3) experience using banana residues on laboratory scale. The disadvantage is the slower process and lower biogas yield.

A slurry reactor is preferred over a system based on dry digestion, because of the low dry matter concentration of banana residues. It is proposed maintain a temperature in the reactor of 33 – 37°C and insulate the reactor. The reactors should have paddle mixers (Figure 5), rather than be mixed by pumping, because of the high viscosity of the slurry. The temperatures in Belize mostly range between 18°C and 33°C and the banana residues will have the same temperature (maybe slightly higher). When it is mixed with the same amount of hot water, such that the mixture has a temperature of 37°C, the temperature in the reactor can be maintained at the desired level, the input mixture can be pumped to the digester and the content of the digester can be mixed with paddles. The hot water has to be produced by a boiler that is heated by biogas or the heat from a CHP system.

Two reactors in series, each with a residence time of 25 days, may be best.
56 ton of banana residues per week is 8 ton per day. When 8 ton water is added per day the total input is 16 ton per day. The slurry from the hammer mill is mixed with water and pumped to the first digester (bottom section) via a pipeline. Near to the digester the pipeline has a valve, which can be closed in case of pump maintenance.
The volume of the first digester is 200 m^3 (wet part). The volume of the second digester is 200 m^3 (wet part) as well.

Figure 5: Paddle mixers in a digester (adopted from www.biofermenergy.com).

The reactors may be concrete cylindrical tank reactors, 7 m high, with 6.5 m actual water height, with a diameter of 20 m. The vertical walls and bottom is concrete. The top is not concrete but is a wooden construction of bars which support a flexible EPDM rubber membrane (Figure 6 and Figure 7). The space between the water surface and membrane is expandable and can store 400 m^3 biogas. As concluded above, two or three paddle mixers with slow movement (15 kW) can be put in each reactor. Furthermore an overpressure safety valve and a glass observation window can be installed. Connections in reactor 1: slurry input, digestate output and biogas output. The digestate leaves reactor 1 via a bottom pipeline and introduces the digestate in the second reactor 6.5 meter higher. This guarantees that the first reactor always has a water level of 6.5 m high. Reactor 2 has the same size and the same biogas storage membrane as the first reactor. Connections in reactor 2: liquid flow from reactor 1, digestate output and biogas output. Reactor 2 serves as a second (less active) biogas reactor and as a storage tank for digestate. The digestate leaves the reactor via a pipe with a valve at the bottom of the reactor. The pipeline between the two reactors should be opposite from the inlet pipe at the bottom of the reactor 1. That will reduce residence time variation of biomass particles. When the tank of a truck is filled with 20 - 30 tons of digestate, the water level of reactor 2 will decrease. The water level of reactor 2 is allowed to fluctuate, because of the flexible biogas membrane (balloon). No air will be sucked in, the head space of the reactor will always contain biogas only because of this expandable membrane.

Figure 6: Digester with EDPM rubber cover (adopted from www.biogasnieuws.blogspot.nl/2011_08_01_archive).

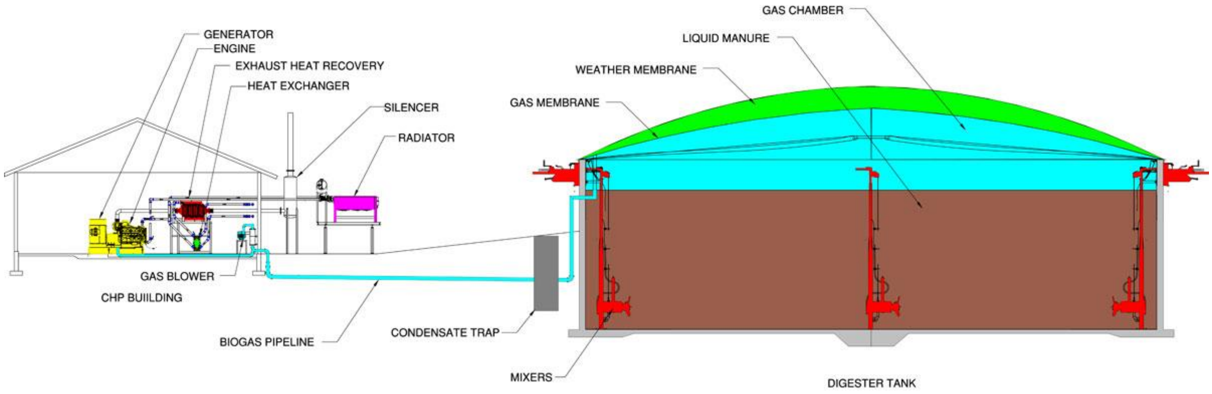

Figure 7: Example of a manure biogas plant with reactor with flexible biogas storage membrane (adapted from www.nothernbiogas.com).

The digestate contains many minerals originating from the biomass and can be used as fertilizer. It will also contain fibers that are not digested. These will improve the soil structure. The digestate can be distributed over arable land.

The digestion process can be started up by filling the first digester with cattle dung slurry and adding the banana residues slowly within a few months up to the design loading rate.

Using the limited information we have it is not known yet which pH will establish in the digester. A pH of 7.5 is optimum. If the pH is lower than 6.5, lime should be added. It is not expected the pH will be higher than 8,5 (the upper limit).

According to Kamdem et al. (2013) 2% of the dry matter of banana residues is nitrogen. Normally in anaerobic digestion most of the nitrogen ends up in form of ammonia nitrogen. It can be calculated that undiluted digested banana residues will contain 3.8 g NH_4-N/l, which is very near to the level for severe inhibition of the methane producing activity (i.e. >4 g/l). This is an additional reason to dilute the material with water. Two times dilution yields 1.9 NH_4-N/l.

Expected gas composition

Bardya et al. (1996) found 60% methane (v/v) in the biogas produced from banana residues.

The NH_3 concentration in biogas will be in equilibrium with a NH_4-N concentration in the water phase of 1.9 g/l. At a pH 7.5 it can be calculated using a pK_a of 9.24 and a Henry's Law coefficient of NH_3 of 60 mol/kg.bar that the expected NH_3 concentration in biogas will be near 41 ppm.

Banana residues contain compounds that contains sulfur, e.g. proteins. No information can be found on this value, but our estimation is that the sulfur content must be near 0.15 % of dry matter. In an influent slurry that contains 9.5% DM, the sulfur concentration may be 143 mg/l. It is assumed that all sulfur will end up as sulfide. The occurrence of species, H_2S, HS^- or S^{2-} depends on the pH and is determined by the acid constant. The H_2S/HS^- acid constant pKa is 6.52. In case the pH of the reactor content is 7.5 it can be calculated that the H_2S concentration is 14 mg/l liquid. The H_2S concentration in the liquid phase of the reactor is in equilibrium with the H_2S concentration of the biogas phase according to Henry's Law. The Henry's Law coefficient for H_2S at 25 ˚C is 0.1 mol/kg.bar, from which it can be calculated that the biogas is expected to contain about 4000 ppm H_2S.

The other part of the biogas is mainly CO_2 with traces of H_2 and N_2, and if the biogas is wet it also contains H_2O.

4.2 Production of biogas from sewage

The cities in Belize (Belize City, San Pedro Town, Belmopan) each collects between 700 and 7000 m^3 of sewage a day. The sewage is currently treated in a facultative lagoon, which means that the energy contained in the sewage is not utilized. As a case the sewage of Belmopan is taken. The current collection amounts 909 m^3 per day and an extension is expected soon with an additional 590 m^3 per day. In total about 1500 m^3 per day, which is about 10500 m^3 per week.
In the report Waste-to-Energy Scoping Study for Grenada it is stated that in the Caribbean region sewage contains 200-250 mg BOD/l and 350-450 mg COD/l. Normally not all COD is converted into biogas, however, it will be more than only the BOD. Using 75% COD conversion and 0.35 Nm^3 methane /kg $COD_{removed}$ and a biogas methane content of 60%:
0.4 kg COD/m^3 sewage x 0.75 x 0.35/0.6 = 0.175 Nm^3 biogas per m^3 sewage is produced. This is not far from the 0.1 Nm^3 methane/m^3 (which may be 0.17 Nm^3 biogas/m^3) mentioned in the Grenada study (Rothenberger, 2015).
The 1500 m^3 sewage per day mentioned may generate 263 Nm^3 biogas per day. When this amount of produced biogas is converted to electricity and heat in a CHP unit, for example the CHP from 2G type FiliUS 107, the following output is generated:

Table 11: Energy production of the proposed system sewage of Belmopan (including expansion of capacity).

Production of	Power	Heat	Hot water (20 → 95)
Per hour	23 kWh	32 kWh	0.10 kg/s
Yearly	192 MWh	270 MWh	3106 ton

Choice of the system
According to Alaerts et al. (1990) anaerobic treatment of sewage is only economically feasible in countries with warm sewage (> 20°C) all over the year (Alaerts et al., 1990). Anaerobic treatment requires less energy, and even produces a fuel (biogas) compared to aerobic treatment. The operational costs are lower, however, in case of high rate reactors, the capital costs are higher. To collect biogas and to limit the size of the systems, high rate anaerobic reactors are recommended.
The best option that combines high performance with low costs is the Upflow Anaerobic Sludge Blanket (UASB) reactor. Alternatives are EGSB (Expanded Granular Sludge Blanket) reactor, IC (Internal Circulation) reactor, fluidized bed and anaerobic filter. For the application in Belmopan, EGSB and IC are too complex,

fluidized beds are too sensitive and anaerobic filters are too susceptible to clogging. In treatment of sewage in tropical regions much more experience is gained with UASB reactors compared with the other reactor types mentioned. We guess hundreds are currently running. In Brazil major cities use UASB reactors to treat sewage and produce biogas and their capacity is up to 360,000 m^3 per day (Giraldo et al., 2007).

Colombia was one of the first countries that adopted UASB technology for sewage treatment. One of the plants in Colombia may act as an example for Belize. It is the Rio Bucaramanga plant. Although treating much more sewage (47,000 m^3/day) than produced in Belmopan, the system uses facultative lagoons as a post-treatment system after the UASB reactor. Belmopan and other cities in Belize already have those facultative lagoons, therefore we can gain a synergy between the new opportunities and the existing structures. It is well known that treatment in anaerobic systems is incomplete and the effluent from such systems cannot be discharged. Therefore, a posttreatment is required to reach the effluent standards. Normally such post-treatment is aerobic. Facultative lagoons contain aerobic and anaerobic parts and will do as well. The Rio Bucaramanga plant comprises a screen, degritting channels, 3 UASB reactors (volume 3300 m^3 each), 2 facultative lagoons (2.7 ha each, which is much too low) and sludge drying beds (Giraldo et al., 2007).

The sewage of Rio Bucaramanga contains 365 mg COD, 171 mg BOD and 225 mg TSS (Total Suspended Solids) per liter and the UASB reactors remove 63% COD, 76% BOD and 76% TSS. The facultative lagoon further decreases these pollutants, resulting in an effluent that contains 30 mg BOD and 30 mg TSS per liter.

Screen

A screen removes larger pieces of floating and suspended solids, like pieces of plastic, rags, paper, leaves and wood. For that purpose a stainless steel bar rack with openings ranging from 1.5 to 3.8 cm can be used.

Degritting channel

In the degritting channel the wastewater flows with a speed at which only sand and related pieces of solids settle to the bottom, while all lighter and smaller suspended solids will stay in suspension (Figure 8). By using a parabolic shape (of the cross-section) the water flow speed (m/s) is always constant and independent of the flow rate (m^3/s), which is useful in case of fluctuating loads. This way sand is removed from the sewage. Sand should be removed to protect pumps and prevent accumulation in reactors.

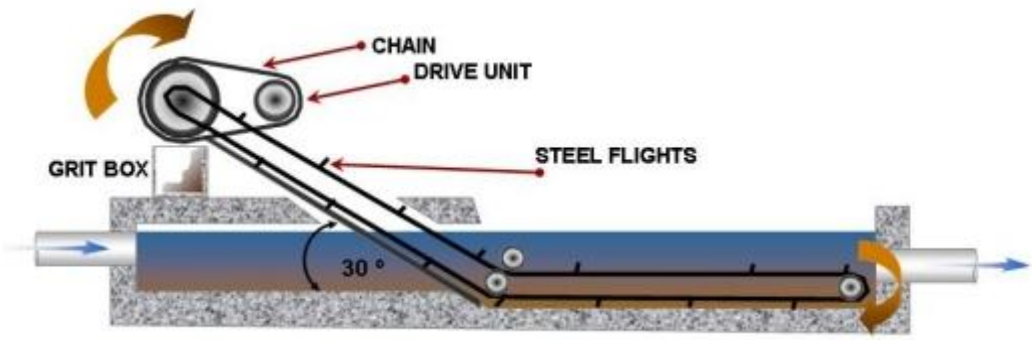

Figure 8: Degritting channel (adopted from www.ewia.co.za).

Equalisation tank

In case the sewage flow rate fluctuates within a day, an equalization basin is required as a buffer. The next step (UASB reactor) can only accept maximum 2 times the design flow rate during peak loading. If the peaks are higher, a basin should be constructed with sufficient storage capacity to shave the peaks. The volume depends on the flow rate pattern, but may be 1/3 of the daily sewage volume, i.e. 500 m^3.

Pumps

In Belmopan and other cities in Belize, an existing system for sewage treatment is present. This system may comprise a pump for lifting the water and several basins in which the water flows by gravity. The introduction of additional unit operations such as UASB reactor and degritting channel may require an additional lifting of water. Such lifting can be carried out by end suction centrifugal pumps with open impellers (to avoid clogging) or Archimedes screws. More than one pump should be installed to anticipate on maintenance breaks. It should be avoided that the anaerobic reactor (see next section) has a bottom section on ground level and that the top is, as a consequence, 6 meters above ground level. Lifting the water 6 meter would consume a considerable amount of energy, and in case the anaerobic reactor effluent falls down a pipe 6 meter again to a lagoon on ground level, a lot of energy is lost. Therefore, if possible, the anaerobic reactor should be placed in a hole in the ground, such that the top section (effluent gutter) is near ground level.

The UASB reactor

In a UASB reactor water flows up through a layer (a bed) of anaerobic sludge (Figure 9 and Figure 10). This anaerobic sludge contains the bacteria that can convert organic material into biogas. The sludge can be present in form of flocs or granules. The sludge is able to settle in an upflow stream of water. The internals comprise three-phase separators: steel or plastic funnels that collect the gas (from the rising bubbles). The space between the funnels act as sludge settling zones. This way water, sludge and gas are separated. The water level is controlled by the position of the effluent gutters.

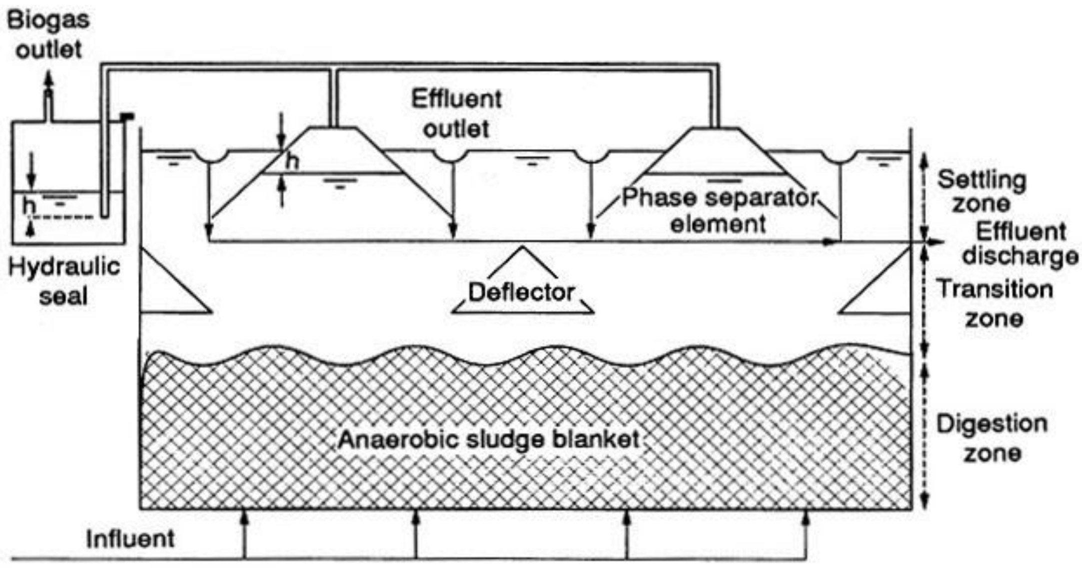

Figure 9: UASB reactor (adopted from www.lippsilos.com).

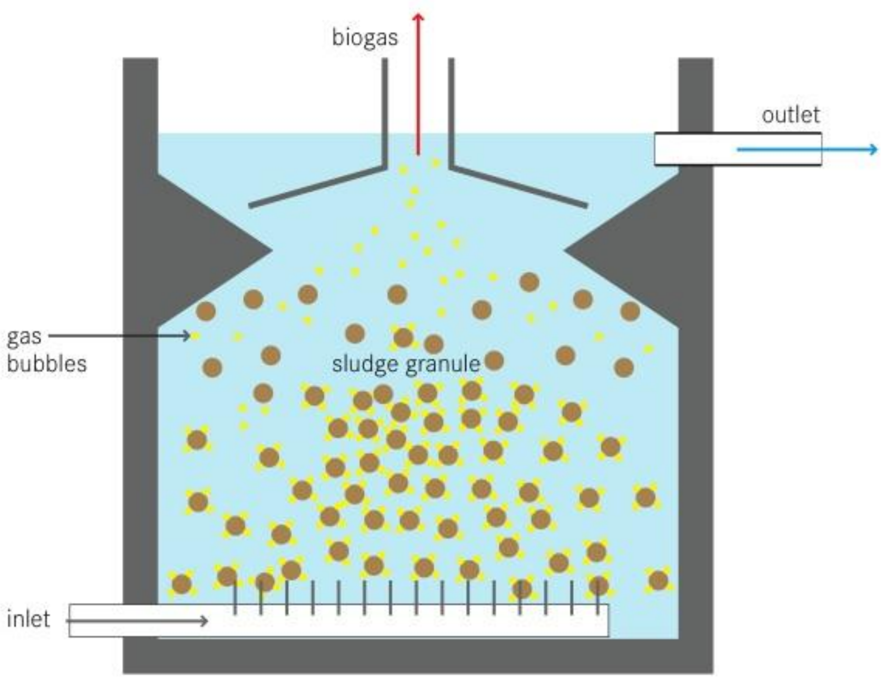

Figure 10: UASB reactor (adopted from www.ethosbolivia2013.blogspot.nl/2013/06/0roject-update-1).

The inlet is a tube with branches. Every square meter on the bottom should have a point at which the sewage is introduced (the open end of a pipe). This way the sewage is equally distributed over the bottom of the reactor before it flows up.
Most UASB reactors for sewage have a hydraulic residence time (HRT) of 6 to 8 hours. In Rio Bucaramanga this HRT is 5.2 hours. For Belmopan 8 hours is recommended, to be safe, because of expected lower temperatures and flow rate fluctuations, and to get a higher COD removal, e.g. 75%. The water height of the reactor can be 5 m. The addition of 1 m free board makes a total of 6 m. Treating 1500 m^3/day requires a reactor volume (wet part) of 500 m^3 and a bottom surface area of 100 m^2. The reactor may be a square tank (10 x 10 x 6 m) with effluent gutters in parallel every 2 m.
The reactor is started up using sludge from another UASB/sewage plant and start-up takes 2 months. However, in case such sludge is not available, cow dung should be introduced in the reactor and the loading with sewage should be slowly increased over a period of many months.
The sludge production in the UASB reactor is normally 0.01 kg VSS per kg $COD_{removed}$. In the Belmopan case the expected sludge production is
1500 m^3/d x 0.4 kg COD/m^3 x 0.75 x 0.01 = 4.5 kg/day
This is very low and to make operation easy it can be recommended not to remove sludge actively from the reactor, but let it accumulate and flow over in the effluent gutter. The sludge will end up in the facultative lagoon, together with the other suspended solids (which is a larger mass), from which it will be removed.

Gas holder

To buffer and store gas between production in the UASB reactor and the utilization, a gas holder can be used. Possible models are the floating gas holder (Figure 11) in which a metal cylinder that is open at the bottom and closed at the top floats in a basin filled with water, or various types of bags, e.g. polyester fabric bags both sides coated with PVC (Figure 12 and Figure 13). For the Belmopan case a gasholder volume of 100 m^3 can be recommended.

Figure 11: Floating gas holder (adopted from www.alibaba.com).

Figure 12: Gas bag (inner and outer membrane) (adopted from www.gticovers.com).

Figure 13: Gas bag with single membrane (adopted from www.alongenvirotech.en.made-in-china.com).

Facultative lagoons

Lagoons can be used to further treat the effluent from the UASB reactor in order to reach the effluent standards and reduce the concentration of pathogens. Wastewater treatment lagoons are basins with a large surface area. A high residence time (at least one month) is used to convert COD, BOD and biologically oxidize ammonia and sulfides. Oxygen supply occurs by natural diffusion and/or production by algae and/or by the action of surface aerators. Facultative lagoons

have aerobic zones, mainly in the upper layer, and anaerobic zones, mainly in the bottom layer, and both zones are active in biological conversion.
The design rules for facultative lagoons are:

- Hydraulic residence time between 5 and 30 days
- Depth between 1.2 – 2.4 m
- Surface loading rate between 23 and 54 kg BOD/acre.day

In Belmopan we expect 1500 m^3 sewage/day. The original expected BOD concentration is about 225 mg/l, but after UASB treatment maybe 54 mg/l is left. Therefore, a lagoon of 3,750 m^2 with a depth of 2 m, a volume of 7,500 m^3 and a HRT of 5 days may be ideal. The surface area is more than enough, but the residence time is the critical design factor.
Sludge can accumulate in the ponds and should be removed from time to time. For that it is good to split up the lagoon in sections. At time intervals a section can be drained and sludge can be removed while the other sections are in operation. This means that the lagoon area and volume should be increased when adding such section.
Despite of the recommendations given above, the lagoon system which is already in operation in Belmopan preferably should be used. If the current lagoon is much larger it means that it can be used for future growth of the capacity.

Sludge drying beds
Sludge drying beds are used to dewater the sludge in large shallow basins. Dewatering takes place by a double action: drainage to the underground (largest part) and evaporation. In practice sludge drying beds can have a bottom layer of sand, artificial media or can be paved. Underdrainage systems should be present. Sand is most used and its layer thickness should be between 23 cm and 30 cm. The sludge layer put on the sand should have a thickness between 20 cm and 30 cm. The dry sludge is removed by shovels and may be used as fertilizer in agriculture.
The surface area required should be between 60 kg and 100 kg sludge dry matter/m^2.year.
Sludge beds are constructed in sections with a wide of 6 m and a length of 6 m to 30 m.
In the case of Belmopan the expected daily amount of sludge accumulated in the lagoons is 35 – 50 kg sludge dry matter, which is 13 – 18 tons per year. Therefore, the sludge drying beds should have a total area of about 200 m^2.

Expected gas composition
The methane content will be near 60%.
Although no data on Belmopan sewage composition are available, it can be expected that the water in the UASB reactor may contain 30 mg NH_4-N and 10 mg sulfide per liter and that the pH is 7.2.
The NH_3 concentration in biogas will be in equilibrium with a NH_4-N concentration in the water phase. At a pH 7.2 it can be calculated using a pK_a of 9.24 and a Henry's Law coefficient of NH_3 of 60 mol/kg.bar that the expected NH_3 concentration in biogas will be near 0.3 ppm.
The occurrence of species, H_2S, HS^- or S^{2-} depends on the pH and is determined by the acid constant. The H_2S/HS^- acid constant pKa is 6.52. In case the pH of the reactor content is 7.2 and the total sulfide concentration is 10 mg/l it can be calculated that the H_2S concentration is 2.2 mg/l liquid. The H_2S concentration in

the liquid phase of the reactor is in equilibrium with the H_2S concentration of the biogas phase according to Henry's Law. The Henry's Law coefficient for H_2S at 25 ˚C is 0.1 mol/kg.bar, from which it can be calculated that the biogas is expected to contain about 633 ppm H_2S.
The other part of the biogas is mainly CO_2 with traces of H_2 and N_2, and if the biogas is wet it also contains H_2O.

4.3 Biogas upgrading

The composition of raw biogas depends on the source of the biogas. Although the composition can vary strongly for individual cases, raw biogas typically contains 60% methane, 40% carbon dioxide (CO_2), and other impurities like hydrogen sulfide (H_2S), ammonia, nitrogen, oxygen, and water vapor. Before the raw biogas can be used for either transport fuel or production of heat and power, it has to be upgraded to the desired specifications. Important steps in the upgrading chain are the removal of H_2S (for every application of the gas) and CO_2 (usually not required for CHP usage). The most common upgrade technologies for H_2S and CO_2 removal are:

a) gas absorption: chemical (reaction, i.e. amines), physical (organic solvent), water scrubbing;
b) adsorption: pressure swing adsorption, vacuum-PSA;
c) selective membranes; and
d) cryogenic.

Depending on the applied technique the following aspects (concerns) have to be taken into account: methane losses, use of chemicals (i.e. solvents), need of electricity, and heat needed for regeneration.
When the biogas is going to be used in a CHP unit to produce power and heat, which is the anticipated use in Belize, usually the CO_2 does not need to be removed. Dedicated biogas engines can cope with gas mixtures with a composition typically in the range of 50–70% methane and 30–50% carbon dioxide.

Banana Waste
In case of the valorization of Banana waste, the main contaminants that are present when biogas is produced, next to carbon dioxide, are ammonia and hydrogen sulphide. Clearly, with these contaminants has to be dealt with, from the perspective of health as well as the durability of equipment (corrosiveness). Based on the possibility to collect the residues from 8 farms, 13 Nm^3 biogas per hour can be produced.
Since the expected amounts of ammonia are rather low (in the order of 40 ppm), ammonia can be separated when the gas is dried or it may be removed when it is further upgraded, so in combination with H_2S and/or CO_2 removal. A separate cleaning step for ammonia is therefore not necessary.
The expected amounts of H_2S are relatively high (in the order of 4000 ppm) meaning that a dedicated H_2S removal process is required. The most simple solution is an activated carbon adsorption bed. The carbon, however, cannot be regenerated and has to be disposed of as chemical waste. This implies high cost to replace the spent carbon with fresh carbon.
Another solution to remove H_2S from the biogas is a conventional scrubber process using a washing fluid. Several options can be considered:

- Chemical scrubber using sodium hydroxide (caustic soda) as absorbing solvent (Mamrosh 2008). Because of the presence of CO_2 the contact time has to be limited to minimize the CO_2 absorption: H_2S is much faster absorbed than CO_2 at high pH levels. Depending on the operation conditions, products that are formed are sodium bisulfide (NaHS) and sodium sulfide (Na_2S), which can be valuable products.

- Chemical scrubber based on a liquid redox system using a chelated iron solution to convert H_2S to elemental sulfur. TNO has developed a regenerative H_2S removal technology that uses an absorption solution comprising an oxidising agent Fe^{3+}NTA that oxidises H_2S into elemental sulfur. The process is schematically presented in Figure 14. The reduced agent Fe^{2+}NTA is regenerated by reaction with oxygen. The absorption solution also contains a radical scavenger resulting in a longer lifetime of the solvent. A variant of this process is the LO-CAT® process that is commercially available by Merichem (see reference).
- Biological scrubbers using bacteria to convert the H_2S to sulphates. Commonly used bacteria for this purpose are from the genus *Thiobacillus*. The advantage above chemical scrubbers is obviously that the biological scrubber does not require chemicals. The disadvantage is that biological scrubbers are less robust meaning that it is more difficult to cope with varying/changing conditions such as the H_2S concentration. A combination of a caustic scrubber and biological regeneration is the THIOPAQ® process provided by Paques (see reference). In this case the H_2S is absorbed in the liquid forming sulphide (HS^-), followed by oxidation of the sulfide into elemental sulphur by autotrophic bacteria.

A more detailed technical and economic analysis is required to determine whether or not activated carbon is a suitable option or which one of the scrubber options is to be preferred.

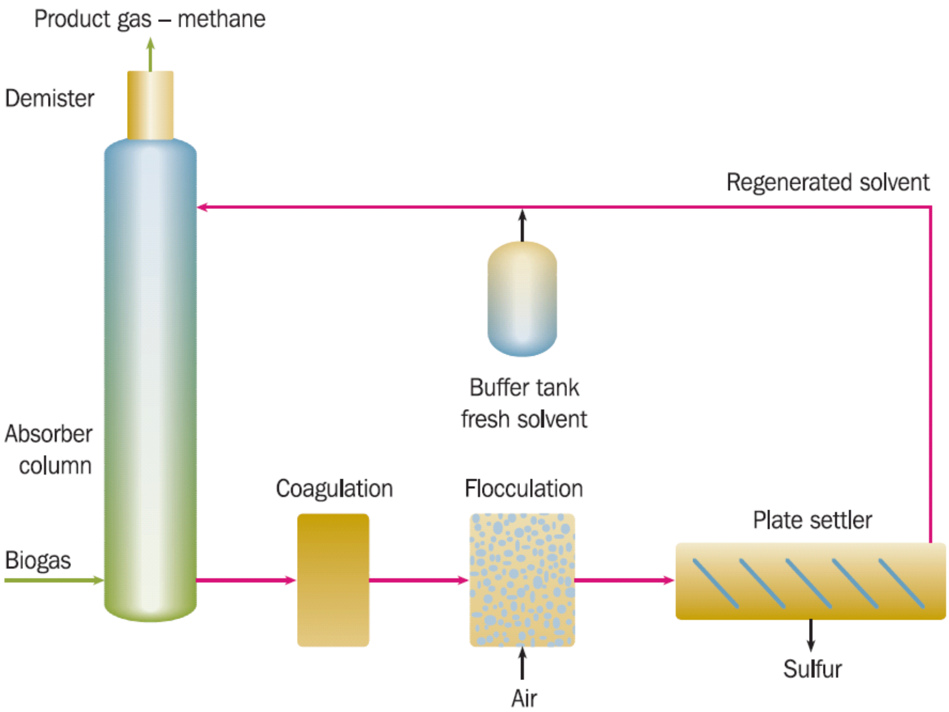

Figure 14: Scheme of the TNO desulfurization process.

Sewage waste
In case of the valorization of sewage waste, the main contaminant that is present when biogas is produced, is hydrogen sulphide. In contrast to the case banana waste, ammonia is hardly present. The expected amount of H_2S, around 633 ppm, is still too high to be used in CHP units, meaning that reduction of the H_2S concentrations is required. Since the amount of biogas produced is about the same, 11 Nm^3/h, whereas 13 Nm^3/h for the banana case, the same processes can be used as already described in the previous section. However, one additional remark has to be made. Since the concentration of H_2S is about six times lower for the sewer waste case compared to the banana case, an activated carbon adsorption bed may be a convenient solution in this case as well. To answer the question whether or not activated carbon is a suitable option or one of the scrubber options is to be preferred, a more detailed technical and economic analysis is required.

In addition to the digester and upgrading equipment a biogas production plant requires a venting system or flare. In case of system malfunction or excess of gas, the biogas needs to be released in a safe way, i.e. via a flare system that burns all the gas.

5 Synergies and location of a biogas plant

Several options have been identified that provide synergies:

- The waste heat from the CHP might be a possible heat source for industrial cooling or production of hot water via a heat pump, subject to the specific need. Typical coefficients of performance (COP) of 3 up to 5 are feasible. A cooling process can be driven by the available waste heat from a CHP (or from solar energy). This process is known as absorption refrigerator, and can be used to cool bananas or other biomass that needs to be cooled. The heat can also be used when there is a need to dry the biomass resources.

- With respect to banana waste it was mentioned in Chapter 4 that the average amount of waste of one farm is rather small: 7 tons/week per farm with an expected biogas production 1.7 Nm^3/h. This is small for a biogas plant and it should be considered to collect banana waste from several farms and digest the material in a central digester. Most farms are concentrated in the Toledo District and the adjacent Stann Creek District. Concentrated areas of banana farming can be found near Cowpen and Santa Cruz, two communities in Stann Creek, see Figure 15. It must be possible to collect the residues from 8 farms within a circle of 30 km around the biogas plant. This way it may be possible to collect 56 tons of residues per week and produce 13 Nm^3 biogas per hour.

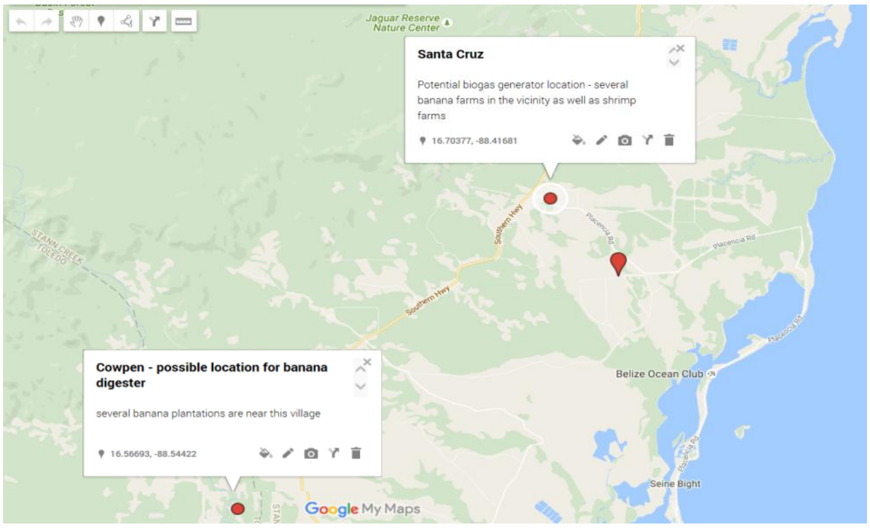

Figure 15: Possible locations for Banana digesters.

- In addition, the digestion of different waste types can be combined in case the same digestion technology can be used. This will help the economy of scale. Moreover, some types of waste that contain too much nitrogen can be mixed with other types of waste to decrease the ammonia-nitrogen concentration during digestion below toxic levels. If in a village several waste streams can be combined and digested in one central digester, the transportation distances are small while the digester can be large enough to gain some economic advantages. Citrus peels (after limonene extraction), banana waste, *Arundo* *donax*, cohune palm nut meal, local fish waste, shrimp heads, *Leucaena,* sargassum*,* roadside green and yard waste, manure, organic household waste and vinasse can all be mixed and digested in the type of digester presented in section 4.1. This type of digester is also used in Europe for manure-co-digestion in which manure is mixed with grass, whole corn plant, sewage sludge and glycerin.

- With respect to sewer waste it was mentioned in Chapter 4 that Belmopan and other cities in Belize have facultative lagoons. This means synergy can be gained when building a new biogas production site and these existing structures. Facultative lagoons can be used as a post-treatment system after the UASB reactor. It is well known that treatment in anaerobic systems is incomplete and the effluent from such systems cannot be discharged. Therefore, a posttreatment is required to reach the effluent standards. Normally such post-treatment is aerobic. Facultative lagoons contain aerobic and anaerobic parts and will do as well.

6 References

Section 3.2

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